Detached eclipsing binaries as primary distance and age indicators †

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Detached eclipsing double line spectroscopic binaries offer an opportunity to measure directly stellar parameters: mass, luminosity, radius, as well as the distance. The only non-trivial step is the need to determine surface brightness of each component on the basis of something measurable, like the color or the line ratios. Modern model atmospheres provide a fairly good calibration of that relation, but empirical verification is possible, and it is needed to achieve the highest accuracy. When this approach is fully developed the detached eclipsing binaries should provide direct (single step) distances with $\sim 1\%$ accuracy to all galaxies in the Local Group.

Recent discovery of numerous detached eclipsing binaries near the main sequence turn-off points in several globular clusters (Kałużny et al. 1996a,b) will be followed by accurate determinations of distances, masses and luminosities. The empirical the mass - luminosity relation near the main sequence turn-off point will allow accurate age and helium determinations, and a check on the stellar evolution theory.

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1. Introduction

The current status of the extragalactic distance scale and the age estimates for globular clusters is highly unsatisfactory, as statements like: "Big Bang not dead yet but in decline" may appear in one of the most prestigious scientific journals (Maddox 1995). The reason for the "crisis" is the assertion that the best current estimates of the of age the universe, as inferred from the adopted value of the Hubble constant, seem to be in conflict with the best current estimates of the ages of globular clusters. The main problem which leads to the "crisis" is a poor estimate of the errors of both measurements.

Various methods used to measure distances are discussed in section 2. The age estimates are discussed in section 3. The discussion with emphasis on detached, eclipsing, double line spectroscopic binaries is presented in section 4.

2. Distance measurements

The more direct is the distance measurement the more trustworthy it is. The most reliable methods are purely geometrical. These include trigonometric parallaxes, dynamical parallaxes, and methods based on coherent motion of groups of objects: moving (e.g. Hyades, Schwan 1991), rotating (e.g. NGC 4258, Miyoshi et al. 1995), or expanding (e.g. SN 1987A, Gould 1995, and references therein). I shall not discuss the coherent motion methods, as they tend to be applicable to unique objects, and it may be very difficult to verify the assumptions about the type of motion involved. In some cases these methods may provide extremely accurate distances, but the errors are very difficult to asses.

The best trigonometric parallaxes are measured with an accuracy better than 1 mas (cf. Monet et al. 1992, Gatewood et al. 1995), and the number of precise measurements will increase dramatically when the Hipparcos catalog becomes available in 1997. Unfortunately, the accuracy of $\sim 1\%$ can be reached only for distances smaller than ~ 20 pc.

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The range of dynamical parallaxes is considerably larger as a binary orbit of two massive and luminous stars may be much larger than one astronomical unit. The linear separation between two stars on a circular orbit can be written as

$$A = 8.5 \times 10^{13}\ cm\ \left(\frac{M_1 + M_2}{20\ M_\odot}\right)^{1/3} \left(\frac{P_{orb}}{3\ yr}\right)^{2/3} = 5.6\ AU\ \left(\frac{M_1 + M_2}{20\ M_\odot}\right)^{1/3} \left(\frac{P_{orb}}{3\ yr}\right)^{2/3}. \tag{1}$$

The angular separation between the two components is given as

$$\varphi = \frac{A}{d} = 5.4\ mas\ \left(\frac{M_1 + M_2}{20\ M_\odot}\right)^{1/3} \left(\frac{P_{orb}}{3\ yr}\right)^{2/3} \left(\frac{1\ kpc}{d}\right). \tag{2}$$

Adopting 3 mas as the limit of resolution of the present optical interferometers (cf. Shao & Colavita 1992) a massive binary can be resolved out to a distance of $\sim 2kpc$. For the resolved pairs the separation between the images of the two components can be measured with $\sim 1\%$ accuracy.

The radial velocity amplitude of the same binary is given as

$$\frac{K_1 + K_2}{\sin i} = \frac{2\pi A}{P} = 56\ km\ s^{-1}\ \left(\frac{M_1 + M_2}{20\ M_\odot}\ \frac{3\ yr}{P_{orb}}\right)^{1/3}, \tag{3}$$

where i is the inclination of the orbit. If this amplitude is measured with a $\sim 1\%$ accuracy (e.g. with the TODCOR, a two-dimensional correlation technique, Zucker & Mazeh 1994), and the angular separation is known with the same precision, then the distance to the binary can be calculated with a $\sim 1-2\%$ accuracy. While accurate measurement of an angular separation is less difficult than equally accurate measurement of a trigonometric parallax, the need for radial velocity measurements makes this method somewhat more complicated. Yet, the effective range of accurate distance measurement is somewhat larger for the astrometric/spectroscopic binaries than it is for trigonometric parallaxes. Some examples are given by Hummel & Armstrong (1994), Pan (1994), and Tomkin et al. (1995), and references therein.

There is a prospect to extend the range of this method with single line spectroscopic binaries using for reference an unrelated star within $\sim 15''$. According to Colavita (1994) relative astrometry with an accuracy reaching $\sim 10\ \mu as$ can be done from the ground with a 1.5 meter telescope for stars as faint as 16 mag at the wavelength of 2.2 μm. Even the Magellanic Clouds may be within reach for purely geometrical distance determination using astrometric/spectroscopic binaries, and the near future ground based interferometers like SUSI (Davis 1994) and VLT (Bedding et al. 1994).

In order to reach out to globular clusters of the Milky Way, and to galaxies of the Local Group with the existing instruments we have to use methods which are not purely geometrical. The simplest of those involves detached eclipsing double line spectroscopic binaries. Such systems are the main source of accurate information about stellar masses, radii, luminosities and effective temperatures (cf. Andersen 1991, and references therein). The procedure is very straightforward.

When two stars orbit each other in a plane which is close to the line of sight then there are two alternate eclipses, with the primary component eclipsing the secondary, and vice versa. The shape of these eclipses provides the information about fractional radii of the two stars: $r_1 = R_1/A$ and $r_2 = R_2/A$, where A is the separation between their centers. The best results are obtained when the binary is well detached, i.e. when the quantities $r_{1,2}$ are small. In that case the two stars can be assumed to be spherical, and the complications due to mass transfer, gas streams, accretion disks, are absent.

The fractions of total light due to each component, L_1/L and L_2/L, can also be

determined from the light curve analysis. In general the so called "third light" may be present, $L_3/L = 1 - L_1/L - L_2/L > 0$, due to an unresolved companion. This can be determined from an accurate photometric light curve, as there is enough redundancy in the shape of the two eclipses (Dreshel et al. 1989, Goecking et al. 1994, Gatewood et al. 1995). The light curve analysis also provides the values of orbital period, inclination, and eccentricity: P, i, e.

The radial velocity curves provide information about the two amplitudes K_1 and K_2, and the orbital eccentricity. The latter offers a consistency check with the photometry. Given the radial velocity curves, the orbital period and inclination, the size of the orbit can be calculated. Finally, the linear radii of the two stars, R_1 and R_2, can be calculated too.

So far the analysis was purely geometrical. Given good enough photon statistics the errors of all quantities can be reduced below 1% level, as demonstrated by many investigators (cf. Andersen 1991). The next step is the only one which involves physics: the surface brightness of the two components must be estimated on the basis of the observed colors, spectral line ratios, or by whatever means. Let these two quantities be F_1 and F_2. Given those, the absolute luminosity of each star in the observed photometric band can be calculated as:

$$L_1 = 4\pi R_1^2 F_1, \qquad\qquad L_2 = 4\pi R_2^2 F_2. \tag{4}$$

The flux of radiation from each star at the telescope is directly measured as $F_{1,tel}$ and $F_{2,tel}$. Therefore, the distance between each star and the telescope can be calculated:

$$d_1 = \left(\frac{L_1}{4\pi F_{1,tel}}\right)^{1/2} = \left(\frac{F_1}{F_{1,tel}}\right)^{1/2} R_1, \quad d_2 = \left(\frac{L_2}{4\pi F_{2,tel}}\right)^{1/2} = \left(\frac{F_2}{F_{2,tel}}\right)^{1/2} R_2. \tag{5}$$

In these equations the two stellar radii follow directly from the analysis of the photometric and radial velocity curves. Naturally, the two values for the distance, d_1 and d_2, should be the same, within errors. The procedure can be repeated for many photometric bands, and all distance determinations should be the same, within errors. For any well observed binary a considerable redundancy is provided by this method.

While in principal any photometric band should yield the same distance, some bands are better than others. The two main difficulties are: the calibration of the surface brightness scale (related to the effective temperature scale, cf. Böhm-Vitense 1981), and the correction for interstellar reddening. Both are minimized in the infrared, where the surface brightness is proportional to the first power of effective temperature, and the interstellar reddening is the smallest. Naturally, the estimate of the effective temperature and the reddening should be done in the part of the spectrum which is most sensitive to these two quantities, i.e. either in the ultraviolet or in the blue part of the spectrum.

The first case of a similar procedure was published many decades ago by Stebbins (1910). At that time the trigonometric distance, the photometric orbit and the radial velocity curves were well measured for the nearby binary β Aurigae, and Stebbins used those measurements to determine the surface brightness of the two identical components. Today the relation between the spectrum and surface brightness is reasonably well known from theoretical models (cf. Kudritzki & Hummer 1990, Kurucz 1992, Buser & Kurucz 1992, Sellmaier et al. 1993). An example of practical application of the eclipsing binary method is provided by Milone, Stagg & Kurucz (1992), who determined the distance to the binary system AI Phoenicis to be 170 ± 9 pc.

The theoretical relation between the stellar spectrum (or color) and surface brightness should be verified empirically. The best opportunity is provided by the stars for which angular diameters were measured (cf. McAlister 1985, Shao & Colavita 1992, and ref-

erences therein). It is my impression that current accuracy is better than $\sim 5\%$ for the value of effective temperature over a broad range of spectral types, and there is good prospect for making it much more accurate.

Somewhat similar but far more complicated, and also far more popular, are Baade-Wesselink and Barnes-Evans methods (cf. Welch 1994, Feast 1995, Walker 1995, and references therein) as applied to pulsating stars. One of their weak points is the same as the only weak point of the eclipsing binary method: it is necessary to infer stellar surface brightness from the spectrum (color or line ratios). However, the B-W and B-E methods have additional weaknesses of their own: the spectrum of a pulsating star is never strictly in a hydrostatic equilibrium, the measured radial velocity has to be converted to the radial velocity of stellar expansion or contraction, the optical depths at which the lines and the continuum are formed are not fixed with respect to matter.

A related Expanding Photosphere Method is used to determine distances to Type II supernovae (cf. Schmidt, Kirshner & Eastman 1992, and references therein). It suffers from all the ailments of the B-W and B-E methods. In spite of all the problems the actual results for cepheids and for supernovae are very encouraging, as presented by Kirshner (1996) and Tanvir (1996). Therefore, there is every reason to expect that the simpler and more direct method of measuring distances to detached eclipsing binaries will be even more successful, as pointed out by Guinan, Bradstreet, & DeWarf (1995), Gimenez et al. (1995), Bradstreet et al. (1995), and Paczyński (1996a).

A preliminary estimate of the LMC distance modulus using detached eclipsing binaries is $(m-M)_{LMC} = 18.6 \pm 0.2$ (cf. Guinan et al. 1995). This accuracy is not very impressive, but it will be greatly improved in the next few years. There are many developments which lead to this optimism.

Well detached eclipsing binaries are difficult to find because they are so well detached, and hence their eclipses are very narrow. With the massive CCD photometry developed in the last few years as a by-product of microlensing searches (cf. Paczyński 1996b, and references therein) tens of thousands of variable stars were discovered. The first catalogs of eclipsing binaries were already published (Grison et al. 1994, Kałużny et al. 1996a,b, Udalski et al. 1994, 1995a,b, 1996). The large number of objects makes it possible to select the most promising systems for the more detailed studies. The best binaries have narrow and deep primary and secondary eclipses, indicating that the two stars are pretty similar, and their radii are much smaller than their separation. Also, no variability should be present outside the eclipses, indicating that the proximity effects are small, and there are no major spots on the stellar surfaces. The search for such systems can be readily done with a 1-meter, or even smaller telescope, but a large area CCD camera and dozens of observing nights are necessary, as demonstrated by the microlensing searches..

For a subset of promising systems the accurate photometry should be done on a medium size telescope, so that photon noise is eliminated as a significant source of errors. When a photometric orbit is obtained it should become clear if the system is indeed simple, i.e. can the shapes of both eclipses be accurately fitted, and can the "third light" be accurately determined. Presumably, only some of the systems with accurate photometry will turn out to be suitable, i.e. will provide very accurate values for the fractional radii of the two components, as well as accurate measurement of the fraction of light from each component.

The third stage is the determination of the best possible radial velocity curves and the spectral measurement. The largest telescopes are required for this step to provide a very high S/N. Accurate measurements of radial velocities of both components are now possible with the recently developed TODCOR method (Zucker & Mazeh 1994, Metcalfe et al. 1995). Relative temperatures for cool stars can be determined spectroscopically to

30 K accuracy (Sasselov & Lester 1990), and the prospect to have a very accurate absolute calibration for early type stars are also good (E. Fitzpatrick, private communication). Note, that surface gravity follows directly from the values of masses and radii, i.e. it is measured directly for the components of eclipsing binaries. Therefore, the temperature and the chemical composition are the only parameters which have to be inferred from the spectra (or colors).

While the determination of interstellar reddening is best done in the blue or even UV part of the spectrum, the infrared K-band measurements are the least affected by the reddening and effective temperature errors (cf. Kelly, Rieke & Campbell 1994, and references therein).

3. Age determinations

The conventional age estimates are based on a comparison between the observed and theoretical color-magnitude diagrams for stars in globular clusters (cf. Chaboyer, 1995, and references therein). The critical region is near the main sequence turn off point (TOP), where stars are similar to the sun. There are two problems with this method: the dependence on the distance and on the "mixing length theory".

The age of a cluster is inversely proportional to the TOP luminosity, $t_{cluster} \sim L_{TOP}^{-1}$ (cf. Bergbush & VandenBerg 1992, Bertelli et al. 1994, or any other set of theoretical isochrones). For a given observed flux of radiation, F_{tel} the luminosity is proportional to the distance square, $L_{TOP} \sim d_{cluster}^2$. Therefore, the age estimate is inversely proportional to the distance estimate,

$$t_{cluster} \sim d_{cluster}^{-2}. \tag{6}$$

If the distance is known to 10% accuracy then the age is known to 20%. It is clear that for the ages to be measured accurately, the distances have to be known even more accurately. This is not a fundamental problem, but it has to be faced and solved.

There are various attempts to circumvent the distance uncertainty. For example, one may use the magnitude difference between the horizontal branch and the TOP. If that was to be taken seriously, and if $\sim 10\%$ errors in the ages were believable, then one could use the eq. (1) to measure distances to clusters with $\sim 5\%$ accuracy. I am not aware of this approach ever used to measure distances. Apparently, the accuracy of age estimates is not taken seriously.

The second, more fundamental problem with the color-magnitude diagram is its dependence on the "mixing length theory" of sub-photospheric convection. The radii of the models, and their effective temperatures, and hence colors, depend on the assumed efficiency of convection through the choice of α parameter. In practice the value of α has to be obtained empirically. There is no reason for this parameter to be constant throughout the color - magnitude diagram. In fact, theoretical isochrones which fit the TOP for some adopted value of α are systematically different from the observations in the subgiant region (e.g. Bergbush & VandenBerg 1992). Various new, more sophisticated models of convection are being developed (Caloi et al. 1996, Canuto 1996, Canuto et al. 1996, Spruit 1996), and it is clear that the shape of isochrones on the color-magnitude diagram depends on the formulation of the theory. As long as a quantitative theory of convection is not available the use of color-magnitude diagrams is subject to errors which are very difficult, perhaps impossible to estimate.

The distance determination to globular clusters can be made more accurate using detached eclipsing binaries. Five such binaries were recently discovered near the main sequence turn-off point in Omega Cen (Kałużny et al. 1996a,b), and five more detached

eclipsing binaries were found in M4 (Kałużny & Thompson 1996). The search will no dobt be extended to many more clusters. Following the procedure described in the previous section the distances to those globular clusters will become known with a few percent accuracy, perhaps even $\sim 1\%$ accuracy will be reached. This will take care of one major contribution to the age uncertainty.

Once the masses of binary components are determined, and their bolometric luminosities are measured, it will be possible to use the empirical mass-luminosity relation to infer the age and helium content by comparing the observed stars with the standard stellar models, like those of Bergbush & VandenBerg (1992) and Bertelli et al. (1994). For a given chemical composition the mass of TOP stars varies with age according to $M_{TOP} \sim t_{cluster}^{-1/3.7}$. The mass determination is based on the radial velocity curves, with $M \sim K^3$, where K is the radial velocity amplitude. Therefore, the age estimate is given as

$$t_{cluster} \sim M_{TOP}^{-3.7} \sim K^{11}, \tag{7}$$

a very steep relation, indeed. However, the value of $K_{1,2}$ for a binary system CM Draconis has been recently measured with an accuracy of 0.2% by Metcalfe et al. (1996) using the TODCOR method (Zucker & Mazeh 1994). If a comparable precision is reached for binaries in globular clusters then the errors in radial velocity measurements will contribute only $\sim 2\%$ to the age error.

Other parameters being equal the luminosity of the TOP stars is proportional to a high power of the mean molecular weight, $L \sim \mu^7$, and that is strongly affected by the helium content. Therefore, the mass-luminosity relation of the TOP stars can be used to determine not only their age, but also their helium content, assuming that the ratio Z/X is known spectroscopically. Note that stellar luminosity is practically independent of the sub-photospheric convection (Paczyński 1984).

4. Discussion

The existing technology: photometry, spectroscopy, empirically calibrated spectrum - surface brightness relation, offer a prospect of using detached eclipsing spectroscopic binaries for very accurate distance measurements to globular clusters, to the Magellanic Clouds, and even to M31 and M33. There is no fundamental reason why the precision as high as $\sim 1\%$ could not be achieved, with large telescopes providing a large number of photons and a high S/N. The weakest link is the relation between the observed spectrum (colors, line ratios, Balmer jump) and the surface brightness. The best prospect is to use model atmospheres to interpolate between the few most accurate empirical calibrators, which are provided by stellar angular diameters measured with optical interferometers. The errors of estimates of the surface brightness and the interstellar extinction can be minimized with K-band photometry.

This is not a new method. The principle goes back to Stebbins (1910). The method was successfully applied to some bright binaries, like AI Phoenicis (Milone et al. 1992). It was used to estimate the LMC distance (Guinan et al. 1995). However, it is little known, and it is not referenced in major papers, like the review of fundamental parameters of detached binaries (Andersen 1991), or the review of distance determinations to nearby galaxies (Huterer et al. 1995). Nevertheless, this method may be the best for distance measurements to globular clusters and to galaxies of the Local Group. It is likely to be superseded only by some future interferometric measurements.

The single most uncertain element of the method is the relation between the observable spectra (colors, line ratios, Balmer jump) and the surface brightness of binary compo-

nents. The distances to nearby galaxies will be measured using the brightest stars which do not have complications caused by stellar winds, i.e. the early B type stars on the main sequence. Distances to globular clusters will be measured using main sequence (TOP) stars of low and moderate metalicity, i.e. the spectral types F and G. Therefore, the calibration of two ranges of spectral types is most important, the early B type and F-G types.

The masses and absolute luminosities of the TOP stars in globular clusters can be used to determine the ages and helium contents of those clusters if the values of mass and luminosity are available for at least two stars in a given cluster. If more than 2 different pairs of data points are available then the shape of empirical mass-luminosity relation can be used to check stellar models. The poorly understood sub-photospheric convection has practically no effect on the mass-luminosity relation (cf. Paczyński 1984).

In order to take full advantage of the future measurements of masses and bolometric luminosities it is necessary to expand the network of evolutionary tracks to cover both dimensions in the (Y,Z) plane. The models of Bergbush & VandenBerg (1992) and Bertelli et al. (1994) cover just a line in that plane.

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